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Aquifers of Nebraska I: The Codell aquifer in northeastern Nebraska

Dana Divine
University of Nebraska-Lincoln, ddivine2@unl.edu

R. Matthew Joeckel
University of Nebraska-Lincoln, rjoeckel3@unl.edu

Sue Olafsen Lackey
University of Nebraska-Lincoln, slackey1@unl.edu

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Conservation and Survey Division
School of Natural Resources
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Bulletin 7 (New Series)

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ABSTRACT

Herein we present results from the first comprehensive study of the Codell aquifer in Nebraska in support of effective management of that groundwater resource. The Codell aquifer underlies a geologically and geomorphically heterogeneous area of about 460 mi^2 (1,190 km^2) in Boyd and Knox counties. Approximately 70 active registered wells averaging 285 ft (87 m) in depth are screened entirely within the aquifer in this area. These wells have an average pumping rate of about 15 gpm (0.95 L/s) and are 4 in (10 cm) in diameter or less. The aquifer-hosting Codell Sandstone, a member of the Carlile Shale Formation, varies in thickness from approximately 8 to 80 ft (2.4 to 24 m) and is overlain by as much as 50 ft (15 m) of the upper Carlile Shale. The elevation of the contact between the Carlile Shale and the overlying Niobrara Formation ranges from a high of about 1,150 ft (354 m) to a low of approximately 1,080 ft (329 m) at the southern edge of the study area. The top surface of the Codell Sandstone is similar in configuration to the Carlile-Niobrara contact, but there are minor differences in the shapes of these two surfaces. The elevation of the top of the Codell Sandstone ranges from about 1,150 ft (351 m) to 1,070 ft (326 m). Groundwater in the Codell aquifer is under pressure everywhere in the study area, except possibly under the Missouri River Trench, where data are lacking. Groundwater in the aquifer flows northward towards the Missouri River and potentiometric head values range from about 1,320 ft (402 m) to 1,200 ft (366 m), which is typically between approximately 100 ft (30.5 m) and 400 ft (122 m) below ground surface. The steepest flow gradient is 0.002 (13 ft/mi or 2 m/km). Analyses of eighteen water quality samples from active wells in the study area collected during 2015 indicate variable water quality and an overall pattern of elevated total dissolved solids, sodium, chloride, and in some places, sulfate. Groundwater chloride concentrations correlate positively with well depth.

INTRODUCTION

Methods

Geologic logs from registered wells in Nebraska were the primary sources of data used in the geologic and hydrogeologic interpretations presented herein, with geologic logs from test holes and registered wells in South Dakota used to constrain the interpretations in the northern part of the study area. The geologic log recorded for a registered well is the well driller's interpretation of geologic material penetrated during the drilling process. Typically, contractors will use a combination of drilling action and visual inspection of sample return to determine what material they are drilling through. Variations in drilling methods, drilling fluid programs, and the amount of experience a contractor has with bedrock drilling can make a substantial difference in interpretation of lithology.

The inherent variability of geologic data creates uncertainty on the maps presented herein, yet recognizable patterns emerge and provide useful geologic and hydrogeologic information that were previously unavailable. The geologic and hydrogeologic contour maps were made using ESRI's geostatistical analysis ordinary kriging interpolation method (ESRI ArcMap 10.2). Interpolation is a way of estimating values where no data exist, and since all of the data used in this atlas was collected from discrete points (wells), any information at a point without a well must be estimated, and therefore, most of the data presented in the maps are estimates. Kriging is a geostatistical method that assigns weights to values at existing data points based on a pattern of spatial continuity (determined by a semivariogram) and then estimates a best fit surface. The surface estimated by kriging does not necessarily pass through the data points, and because the method seeks to best fit intermediate values, the high and low points in the data set will probably be smoothed out.

The subjective nature of recording and interpreting geologic material has a direct bearing on the accuracy and precision of the figures presented in this publication. The top of Carlile and top of Codell contour maps probably differ from reality because of differences in the way people logged the same sediment and rock types in different wells. A systematic test hole drilling program including downhole geophysical logging would be required to more accurately contour these stratigraphic surfaces.

The static water level map was made using water level information collected between 1996 and 2014 from 70 wells screened entirely in the Codell aquifer, and, therefore, the contours on this map should be interpreted as average conditions during that time span. The well data used to make this map consist of only one water level per well that was measured by the driller at the time the well was installed. Given the scarcity of the data and the fact that the aquifer is not used for irrigation, measurements were used regardless of the month in which they were collected.

Geographic Setting

The Codell Sandstone member of the Carlile Shale Formation is both an aquifer and a petroleum reservoir in the interior of North America. Numerous studies regarding the stratigraphy, petrography, and economic potential of the Codell Sandstone have been published for Kansas, Colorado, Wyoming, and South Dakota (e.g. Busch, 1976; Galperin, 1993; Krueger, 2015; McLane, 1982; Sablina, 1993; Weigand, 1991; Weimer and Sonnenberg, 1983). The Codell Sandstone is a relatively minor aquifer in Nebraska overall, but it is an important source of groundwater locally. Registered well logs indicate the Codell Sandstone supplies groundwater to about 70 active domestic and stock wells in a 460 mi^2 (1,190 km^2) area in eastern Boyd and northern Knox counties (Fig. 1).

The Codell Sandstone and the aquifer that it hosts have not been studied previously in this area because exposures are lacking and subsurface data are limited to registered well logs. The inherent complexity of the Codell Sandstone's shallow-marine depositional environments and the effects of post-depositional structural deformation and erosion further complicate a scientific assessment of the Codell aquifer. Documenting the present state of geological knowledge, areal extent, and hydrogeologic properties of the Codell aquifer is a necessary first step toward more focused data collection and sustainable management in the future.

The area of Nebraska in which the Codell aquifer is used for water supply includes the confluence of the Niobrara and Missouri rivers and the lower reaches of Ponca, Verdigre, and Bazile creeks (Fig. 1). Most of the study area is in a single Major Land Resource Area, the Southern Rolling Pierre Shale Plains, although the eastern part is included in the Loess Uplands and there are small areas classified as Dakota-Nebraska Eroded Tableland (U.S. Department of Agriculture, 2006). Thus, the landscape is generally rolling rather than flat and total relief in the study area exceeds 570 ft (175 m). The dominantly clayey, silty and loamy soils in the study area formed from widespread weathered Cretaceous shale, Quaternary loess, and alluvium (U.S. Department of Agriculture, 2015). Grazing with non-intensive land management is the dominant land use, although cultivated cropland is also present (U.S. Geological Survey, 2011). Average annual precipitation is about 25 in (64 cm) (U.S. Department of Agriculture, 2012). The combined population of Boyd and Knox counties is only about 10,800 people in an area of approximately 1,685 mi^2 (4,365 km^2). The principal towns in the study area are Lynch, Verdel, Niobrara, and Santee, each of which has a population of 370 or fewer (U.S. Census Bureau, 2010).

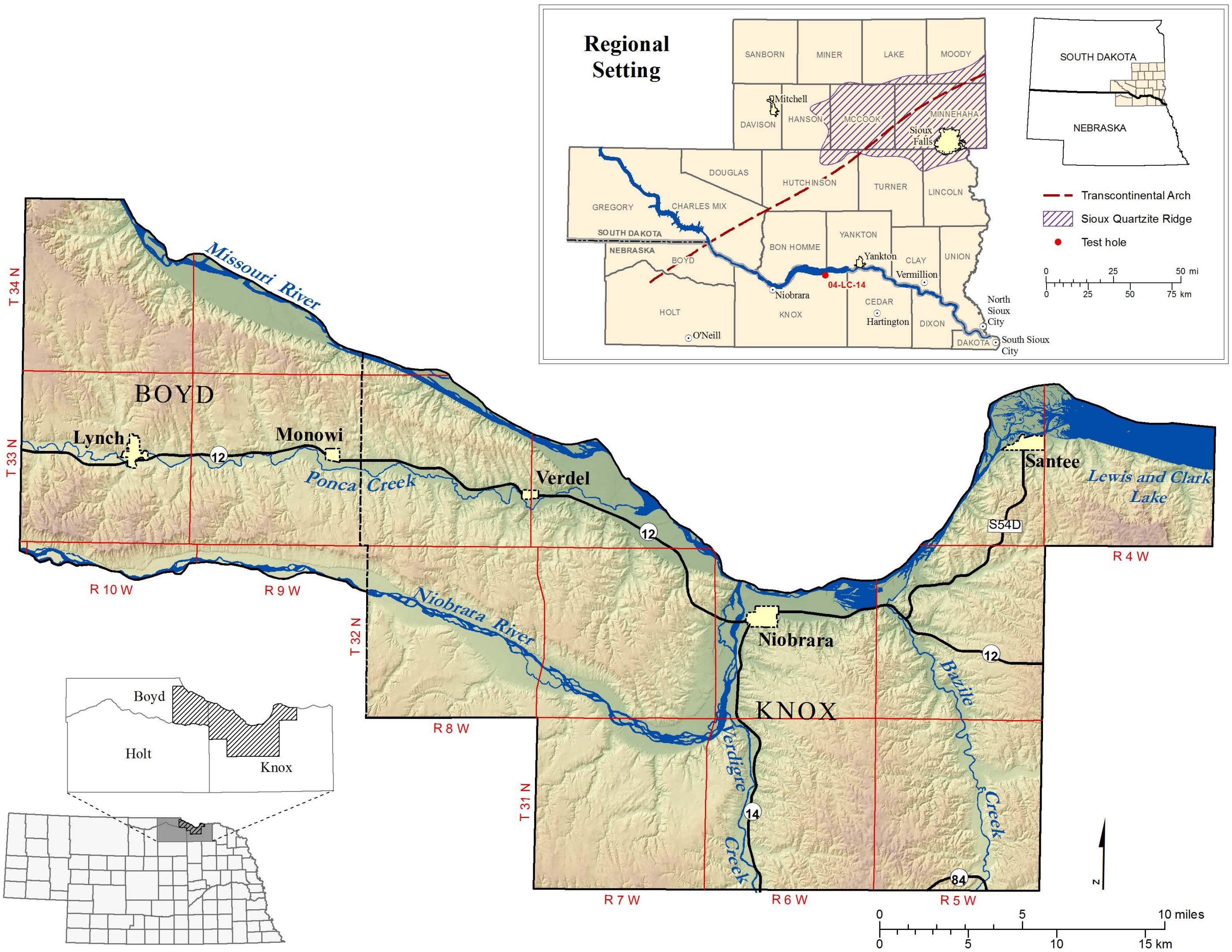


Figure 1. Geographic setting of the study area and environs.

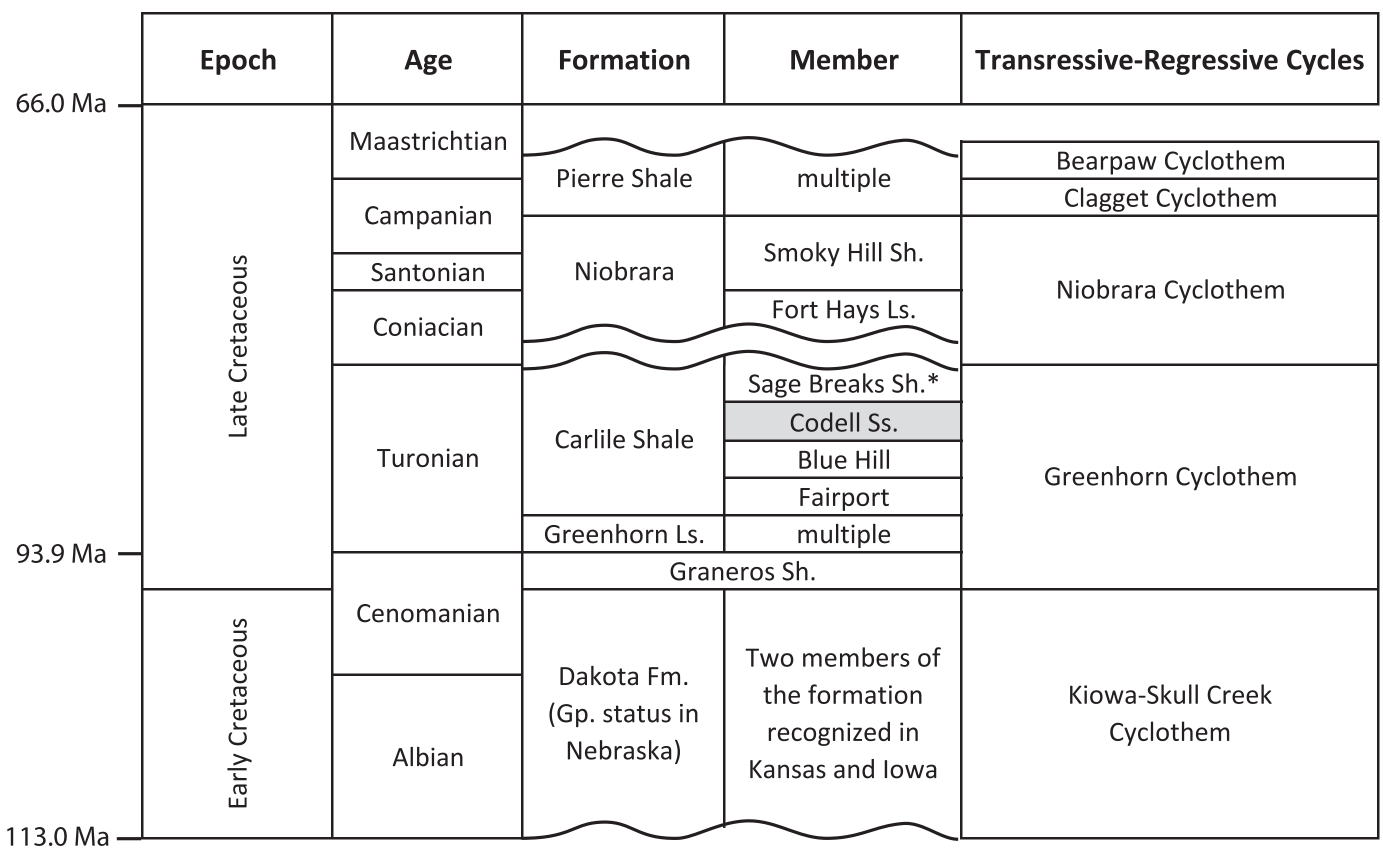
The physical geography of the area is complex due to multiple cycles of Pleistocene glaciation, subsequent eolian erosion and deposition, and the ongoing dissection of the landscape by streams. At its maximum extent during pre-Illinoian times, between 2.5 million and 640,000 years ago, the Laurentide Ice Sheet extended across South Dakota east of the present Missouri River and across eastern Nebraska (e.g. Todd, 1914; Simpson, 1960; Reed and Dreeszen, 1965; Hedges, 1975; Roy et al., 2004; Balco, et al., 2005; Boellstorff, 1978a; Boellstorff, 1978b, Rovey and Bettis, 2014). The present Missouri River Trench, at the northern border of the study area, formed only after the final retreat of the ice sheet from Nebraska.

Stratigraphy and Depositional Environments

Overview of the Western Interior Basin

The Carlile Shale is part of a regionally consistent succession of Cretaceous strata that was deposited in the Western Interior Seaway (WIS) during the middle to late Turonian Stage (e.g. Hattin, 1962). The Cretaceous succession at the eastern margin of the former seaway incorporates the stratigraphic interval beginning at the base of the Dakota Formation (“Dakota Group” of Condra and Reed, 1959) and ending at the top of the Pierre Shale (Fig. 2), although Cretaceous strata older than the Dakota Formation are present in Kansas (e.g. Scott, 1970). The Carlile Shale is underlain by the chalky limestones of the Greenhorn Limestone and overlain by the chalky limestones of the Fort Hays Limestone of the Niobrara Formation (Fig. 2).

Both the Graneros Shale and Greenhorn Limestone, underlying the Carlile Shale (Fig. 2), were deposited during the transgressive phase of the Greenhorn Cyclothem, during which world sea level rose. The Dakota Formation-Graneros Shale contact is conformable and gradational (Merewether, 1983), as is the contact between the Greenhorn and Carlile, with the Pfeifer Shale Member of the Greenhorn Limestone directly underlying the Fairport Member of the Carlile Shale (Hattin, 1962). The Carlile Shale was deposited during the regression of the Greenhorn



* applies in the vicinity of the Denver-Julesburg Basin
Ls = Limestone
Sh = Shale
Ss = Sandstone
Gp = Group
Fm = Formation
Ma = Million years ago

Figure 2. Stratigraphic chart with the Codell Sandstone Member of the Carlile Shale shaded. Undulating lines represent unconformities.

Cyclothem when sea level fell worldwide, and the Codell Sandstone was deposited at or near the very end of that regression (Witzke et al., 1983).

A gap in the geologic record called a lacuna separates the Carlile Shale and the Niobrara Formation, with biostratigraphic zones missing from both formations (Hattin, 1975). Hattin (1962; 1975) showed a progressive truncation of Carlile Shale strata starting in western Kansas spreading to northeastern Nebraska and suggested it as the cause for the lateral separation of the Codell Sandstone between western Kansas and eastern South Dakota and Nebraska. This pre-Niobrara non-deposition and erosion may have been caused by uplift along the Transcontinental Arch and resulted in the truncation of the Upper Carlile, including the Codell Sandstone (e.g. Hattin, 1962; Hattin, 1975; DeGraw, 1975; Busch, 1976; Weimer, 1960).

Data from a Conservation and Survey Division test hole drilled in northeastern Knox County in 2014 (04-LC-14, Fig. 1) reveal that the regional Cretaceous succession in that area is at least 874 ft (266 m) thick, significantly thicker than the estimate provided by Merewether (1983) for the same vicinity. On a geophysical log from this test hole and an electric log from the Denver-Julesburg basin, the Codell is marked by a corresponding decrease in the SP curve and increased resistivity, both similar in magnitude to the overlying Niobrara Formation (Fig. 3). The 2014 log also includes a gamma curve, which shows very definite decreases associated with the sand or sandstone intervals of the Codell.

During the upper middle Turonian, the eastern shoreline of the WIS probably ranged from approximately 101° to 93° west longitude, the most westerly part of this shoreline possibly located near the Oklahoma/Texas panhandles (Fig. 4) (Cobban et al., 1994). The source area for the Codell Sandstone in South Dakota, eastern Nebraska, and Kansas was probably east of the eastern shoreline (Hattin, 1962; Hattin, 1975; Merewether, 1983). At the same time, the western shoreline of the WIS ranged from approximately 115° to 109° west longitude, (Cobban et al., 1994; Weimer, 1960). The source materials for the Codell Sandstone

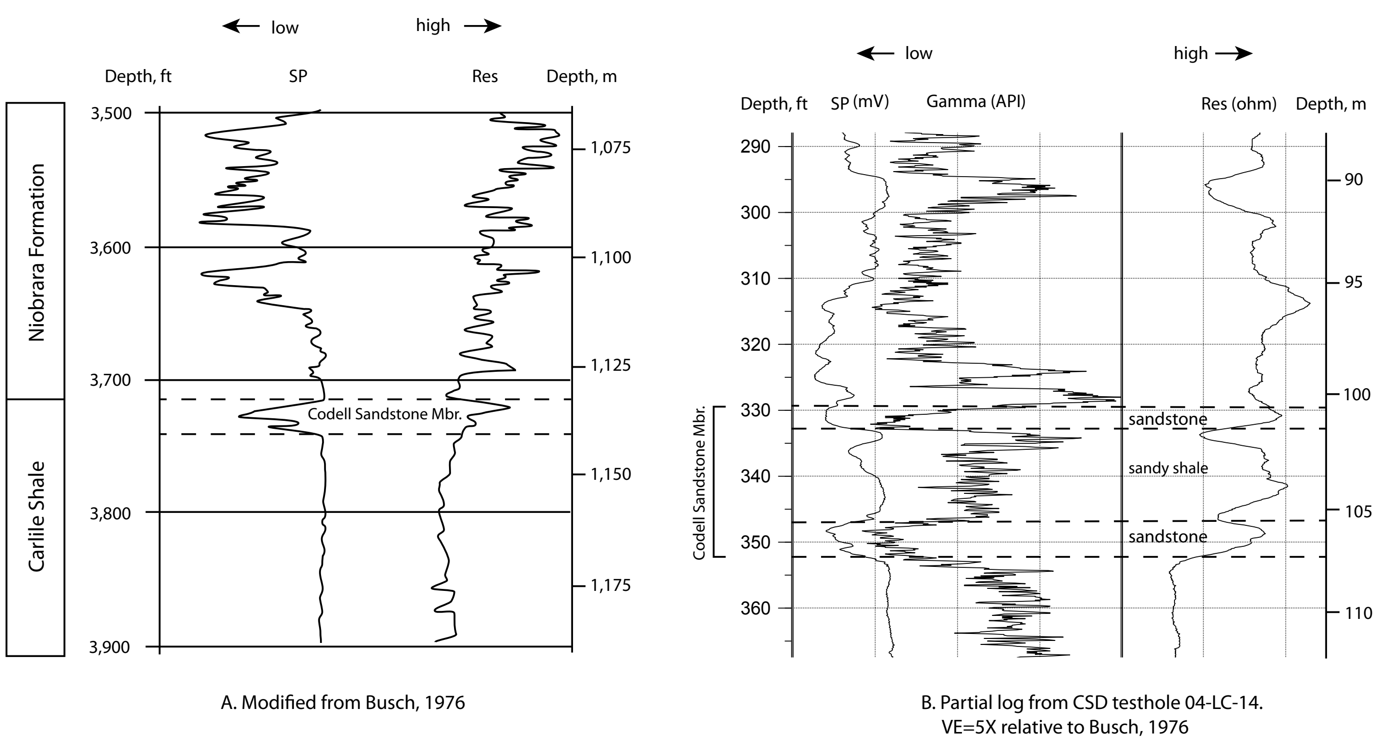


Figure 3. Geophysical logs showing the Codell Sandstone. Log A depicts the Codell Sandstone on the eastern flank of the Denver-Julesburg basin near the Nebraska-Wyoming state line. Log B depicts the Codell Sandstone in Knox County, east of the study area where the Codell is sometimes observed in bore holes but not used as an aquifer.

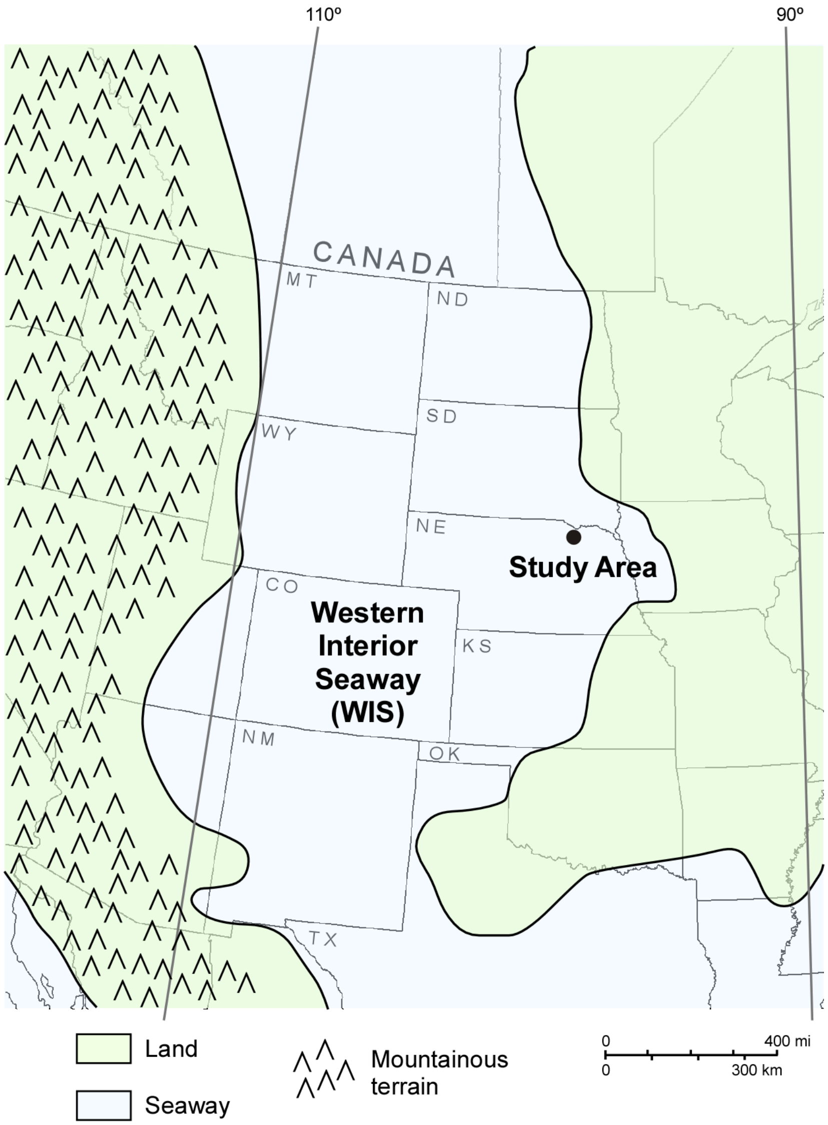


Figure 4. The estimated position of Western Interior Seaway shorelines approximately 85 million years ago. The Codell Sandstone was deposited along both shorelines in different depositional environments from distinct source areas. Adapted from Blakey, 2016.

and its equivalents in Wyoming, Colorado, and western Nebraska originated west of the shoreline and were deposited in a variety of near-shore marine environments (Busch, 1976; Weimer and Sonnenberg, 1983; McLane, 1982; Krutak, undated).

Eastern Side of Western Interior Seaway (WIS)
Condra and Reed (1959) described the Codell Sandstone in Nebraska as a fine-grained sandstone, 5 ft to 10 ft (1.5 to 3 m) thick, which underlies southwestern, western, and northern Nebraska a few feet below the Niobrara Formation. In actuality, along the entire eastern margin of the WIS, the Codell includes siltstone, fine- to medium-grained sand or sandstone, and/or conglomerate (e.g., Jorgenson, 1971; Christensen, 1974; Hedges, 1975; Souders, 1976). The Codell Sandstone near Mitchell, South Dakota (Fig. 1) is crossbedded and coarsens upward from fine-grained sandstone to conglomerate that contains pebbles as much as 2 inches (5 cm) in diameter (Merewether, 1983). The colors of the Codell Sandstone in Nebraska and South Dakota have been described as gray, brown, green, reddish-brown, or black (Condra and Reed, 1959; Hedges, 1975; Christensen, 1974; Kume, 1977).

The depth to the top of the Codell Sandstone from the top of the Carlile Shale, as well as the total thickness of the Codell, vary markedly in Nebraska and South Dakota. Estimates of thickness range from 0 ft to 100 ft (30 m) (e.g. Christensen, 1974; Jorgensen, 1971; Hedges, 1975; Kume, 1977; Souders, 1976, Dreeszen, 1966). The thickness of the Codell in the study area ranges from 8 ft to 80 ft (2.4-24 m). Most sources report that, where present, the Codell is overlain by 0 ft to 50 ft (0-15.2 m) of shale (Christensen, 1974; Jorgensen, 1971; Hedges, 1975), a range of values that was confirmed in the study area.

The Codell Sandstone is known to be widespread in eastern South Dakota, adjacent to the present study area, except over the Sioux Quartzite Ridge (Fig. 1). The formation thins and then disappears westward into central South Dakota (Witzke et al., 1983), and it is very thin or absent both in the western two-thirds of Boyd County (Souders, 1976) and in the eastern half of Knox County, Nebraska. Far southwestward, the Codell serves as an aquifer in parts of six counties in northwestern Kansas (Weigand, 1991), where the type locality is located in Ellis County. The Codell Sandstone Member is generally classified as the uppermost of three members in the Carlile Shale on the eastern side of the WIS (Fig. 2) (e.g. Hattin, 1962; Hattin, 1975; Weigand, 1991), although on the western side the shale that sometimes overlies the Codell is assigned to the Sage Breaks Member (e.g. Weimer and Sonnenberg, 1983; DeGraw, 1975). The Codell Sandstone may appear in the study area as one to three sand or sandstone units separated by thin shale units, which complicates identifying it in well logs and characterizing its hydrogeologic properties.

The paleogeographic setting of the Codell Sandstone on the eastern margin of the WIS is not well resolved (Witzke et al., 1983; DeGraw, 1987). Witzke et al. (1983) suggest that deposition began along the eastern margin and prograded westward into the seaway during a middle Turonian marine regression, in which case the Codell sandstone of the type area in western Kansas is interpreted as the distal, fine-grained, shallow marine sandstone facies of a prograding wedge of clastic sediment. Coarse-grained, crossbedded lithofacies along the shoreline may be marginal-marine and delta-front facies of the same wedge (Witzke et al., 1983; Merewether, 1983). Geochemical analyses of septarian concretions from the Carlile Shale contain indicators of overall upward-shallowing marine conditions and even the development of non-marine environments during Codell deposition (Ludvigson et al., 1994). These results are compatible with the common interpretation of the Codell Sandstone as a wedge of clastic sediment that prograded into the WIS.

Western Side of Western Interior Seaway (WIS)
In the Denver-Julesburg Basin at the western margin of the WIS, the Codell Sandstone gradually coarsens upward and varies in texture from sandy siltstone to coarse-grained sandstone (Krueger, 2015). Codell sandstones in the Denver-Julesburg Basin are usually sublitharenites (sandstone consisting of 5-25% rock fragments with less than 15% mud in in the matrix) to quartz arenites (sandstone consisting of greater than 90% quartz) with subrounded to well-rounded, well-sorted grains and calcite cements (Busch, 1976). Busch (1976) documented diagenetic processes in the Codell including pyrite precipitation, minor limonite staining, and oxidation. In the Denver-Julesburg Basin, the Codell Sandstone is generally light gray to dark gray in color (Krueger, 2015), ranges from 0 ft to 125 ft (0-38.1 m) thick, averaging between 15 ft and 20 ft (4.6-6.1 m) thick (Busch, 1976; Weimer and Sonnenberg, 1983).

On the western side of the WIS, the surface between the Codell Sandstone and the underlying shale is marked by an angular unconformity caused by minor submarine erosion of the marine-shelf prior to deposition of the Codell (DeGraw, 1975; Busch, 1976). The Codell Sandstone has been interpreted as subtidal offshore to lower shoreface marine shelf to shoreline sand that was probably deposited both below and above storm wave base. Various depositional environments have been proposed for that area of the WIS, including barrier islands, lagoon fills, tidal channels and deltas, and offshore bars (Busch, 1976; McLane, 1982; Weimer and Sonnenberg, 1983; Galperin, 1993; Sablina, 1993; Krueger, 2015). The Fort Hays Limestone Member of the Niobrara Formation is known to disconformably overlie the Codell Sandstone and even the lower part of the Carlile Shale due to Cretaceous erosion (e.g., DeGraw, 1975; Busch, 1976). In Wyoming, syndepositional crustal flexure also promoted the erosion of the lower part of the lower Carlile Shale (Weimer and Sonnenberg, 1983).

Structural Geology
Laramide reactivation of the Sioux Quartzite Ridge in southeastern South Dakota (Fig. 1) deformed the regional Cretaceous succession (Fig. 2) into broad synclines north and south of the ridge itself (Koch 1986; Merewether,1983; Bunker, 1981). The axis of the southern syncline plunges to the southwest (Merewether, 1983, fig. 16; Bunker, 1981, fig. 8) and appears to pass near, or even directly through, the present study area. Subsequent to this deformation, late Cenozoic (probably Pleistocene) local erosion further truncated the Codell (e.g. Christensen, 1974), which is absent in the Tyndall-Scotland bedrock valley in Bon Homme County, South Dakota (Jorgensen, 1971), as well as at outcrops along the Missouri River

between Vermillion and Yankton, South Dakota (Merewether, 1983). The erosional surface between the Carlile and the Niobrara has as much as 2 ft (60 cm) of local relief at an outcrop southeast of Yankton (Simpson, 1960). In Colorado, Wyoming, and western Nebraska, the Laramide deformation of Cretaceous rocks created the Denver-Julesburg Basin (e.g. Anderman and Ackman, 1963) and tilted the Codell Sandstone to the southwest to its present configuration as part of the northeast flank of the basin (Busch, 1976).

Figure 5 depicts the structural contour map of the contact between the Carlile Shale and the Niobrara Formation in the study area. The elevation ranges from a high of about 1,150 ft (354 m) above mean sea level to a low of about 1,080 ft (329 m) at the southern edge of the study area. A southerly dip is expected due to the syncline south of the Sioux Quartzite ridge delineated by Bunker (1981) and Merewether (1983), although their maps suggest a southwestern dip rather than the generally due south dip in Knox County shown in figure 5. The scale of mapping between this study and that of Bunker (1981) and Merewether (1983) differs by approximately an order of magnitude, which limits the validity of direct comparison. The structure of the contact may change in Boyd County, but the limited number of data points in the study area makes this speculation impossible to verify at present.

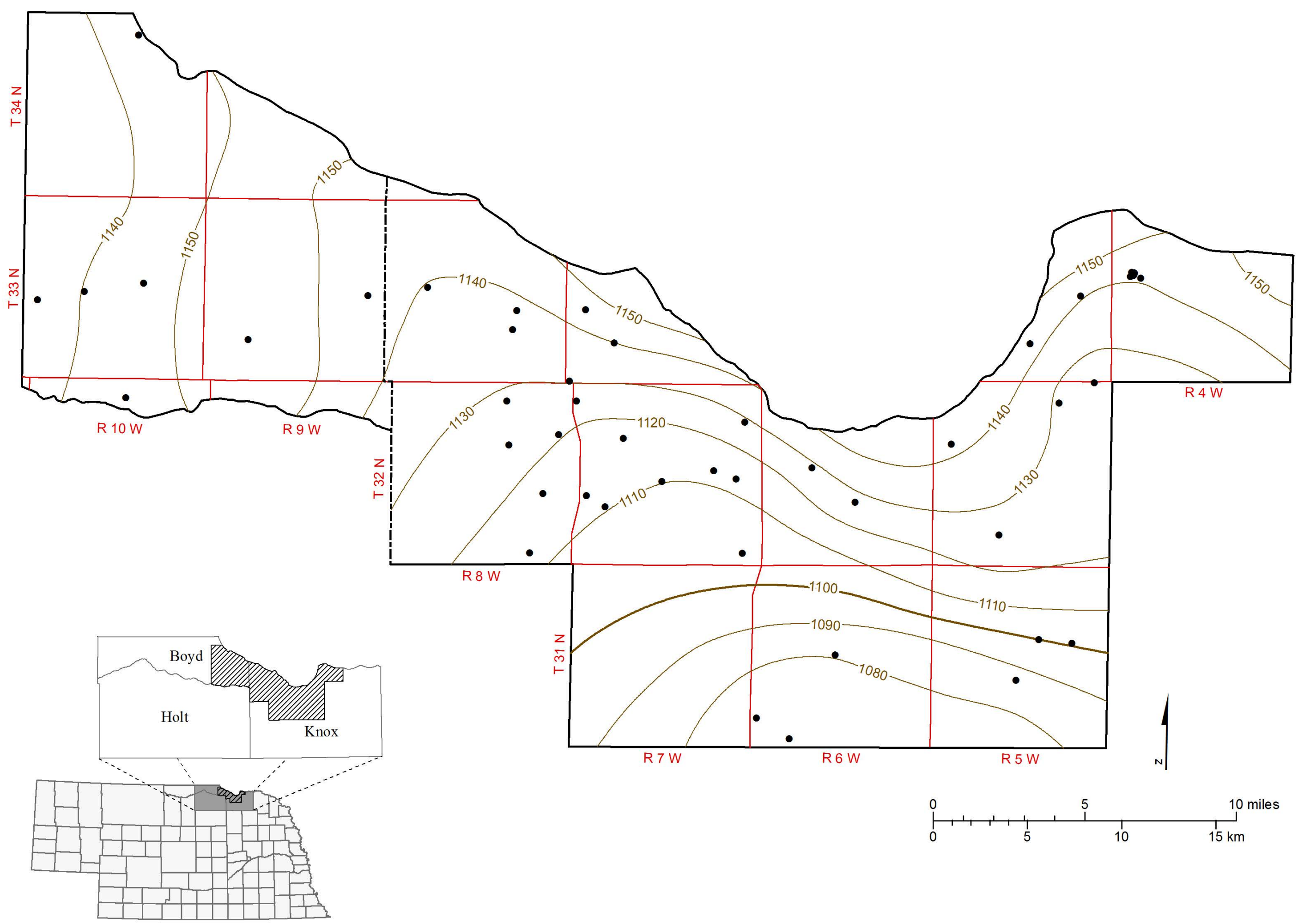


Figure 5. Structure contour map of the estimated Carlile-Niobrara contact in feet above mean sea level. Black dots represent registered wells in which the contact was identified. Contour interval is 10 ft.

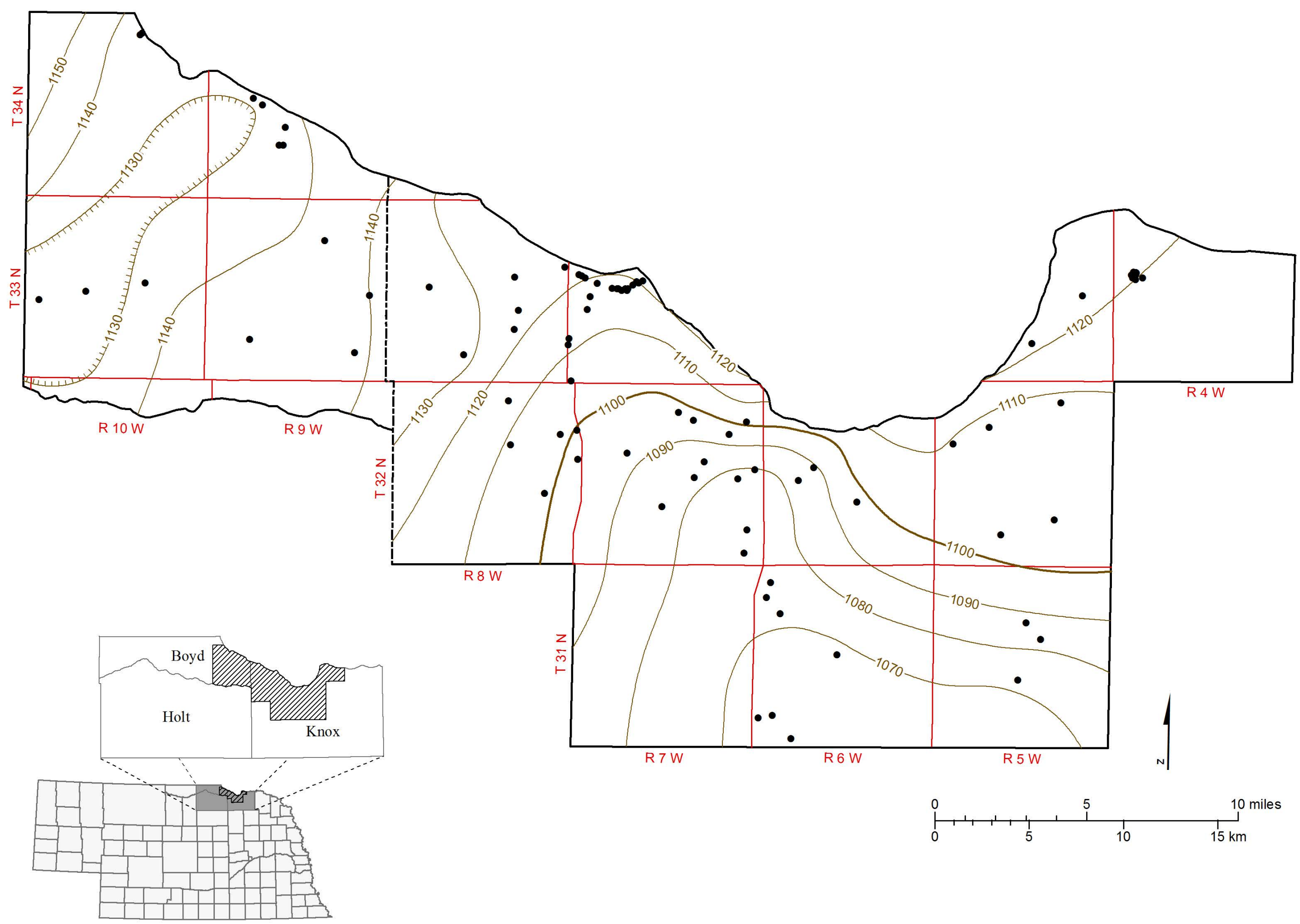


Figure 6. Structure contour map of the estimated top of the Codell Sandstone in feet above mean sea level. Black dots represent registered wells in which the top of the Codell was identified. Contour interval is 10 ft.

Figure 6 depicts the structural contour map of the top of the Codell Sandstone Member. The elevation ranges from a high of about 1,150 ft (351 m) above mean sea level in eastern Boyd County to a low of about 1,070 ft (326 m) in the southern part of the study area. The structure of the top of the Codell is similar to that of the Carlile-Niobrara contact in that they both dip generally south in Knox County, but minor differences between the two surfaces exist. The depth of the top of the Codell below the Carlile-Niobrara contact varies from 0 ft in parts of the western study area to a maximum of about 50 ft (15.2 m) in a small area in the Missouri River valley.

Jorgensen (1971) produced a structural contour map of the top of Codell for Bon Homme County, South Dakota. The elevation of the top of Codell in the Missouri River Trench on his map is generally the same as that depicted on figure 6, which is to be expected. The structural contours in Bon Homme County also generally dip to the south, and show some erosional features (Jorgensen, 1971).

Hydrogeologic Framework

The Codell aquifer is one of four possible sources of groundwater in the study area, the others being, in ascending stratigraphic order: (1) the Maha Aquifer of the Great Plains Aquifer System, locally referred to as the "Dakota aquifer" for the Cretaceous stratigraphic unit that hosts it in eastern Nebraska; (2) outliers of the Miocene Ogallala Group under the dissected plains between Verdigre and Bazile creeks, and also east of Bazile Creek; and (3) Quaternary alluvium in the Niobrara and Missouri river valleys. The Ogallala Group outliers and the regional alluvium are both shallow and easily accessible by drilling, but they have limited areal extents. The "Dakota aquifer" underlies the entire study area and extends well beyond; it produces well yields in excess of 1,000 gpm in the study area (Nebraska Department of Natural Resources, 2014). The top of the "Dakota aquifer," however, is generally at least 700 ft (213 m) below ground surface in the study area and the average well depth is approximately 930 ft (283 m).

The Codell aquifer is much less productive than the "Dakota aquifer," exhibiting average well yield of about 15 gpm (0.95 L/s). Because the Codell aquifer lies at a much shallower depths (averaging about 285 ft or 87 m), however, it is much more easily and cheaply accessed as a source of groundwater. The Codell aquifer is generally confined and pressure head causes the water in wells to rise above the top of the aquifer. According to Kume (1977), the Codell aquifer is unconfined at some locations in the Missouri River valley where it is in direct contact with alluvium. The Codell aquifer is primarily used for domestic

Photo courtesy R.M. Joeckel, Conservation and Survey Division

The Codell Sandstone Member of the Carlile Shale at its contact with the more resistant Fort Hays Limestone Member of the Niobrara Formation in Ellis County, Kansas.

and stock wells, partly because the modest yields are more suited to those uses, but also because water in the aquifer tends to have high sodium and salinity hazards that make it unsuitable for irrigation (Jorgensen, 1971; Kume, 1977; Souders, 1976; Weigand, 1991).

Potentiometric Surface

Figure 7 depicts the static water level elevation in the Codell aquifer and indicates that the groundwater flow in the study area is north-northeasterly toward the Missouri River Trench. Outside the trench the static water level contours represent a potentiometric surface, which ranges from a low of about 1,200 ft (366 m) above mean sea level in the northeastern part of the study area to a high of about 1,320 ft (402 m) in the southern part of the study area. The pressure gradient of 0.002 is relatively steep (13 ft/mi or 2 m/km). In South Dakota, the gradient in the Codell aquifer is also toward the Missouri River Trench, which is probably a natural discharge area (Jorgensen, 1971; Kume, 1977). Registered well logs from Nebraska indicate that the Missouri River alluvium is in direct contact with the Codell at some locations, so it is probable that the river is also a discharge point for groundwater flowing north through the Codell aquifer from Nebraska.

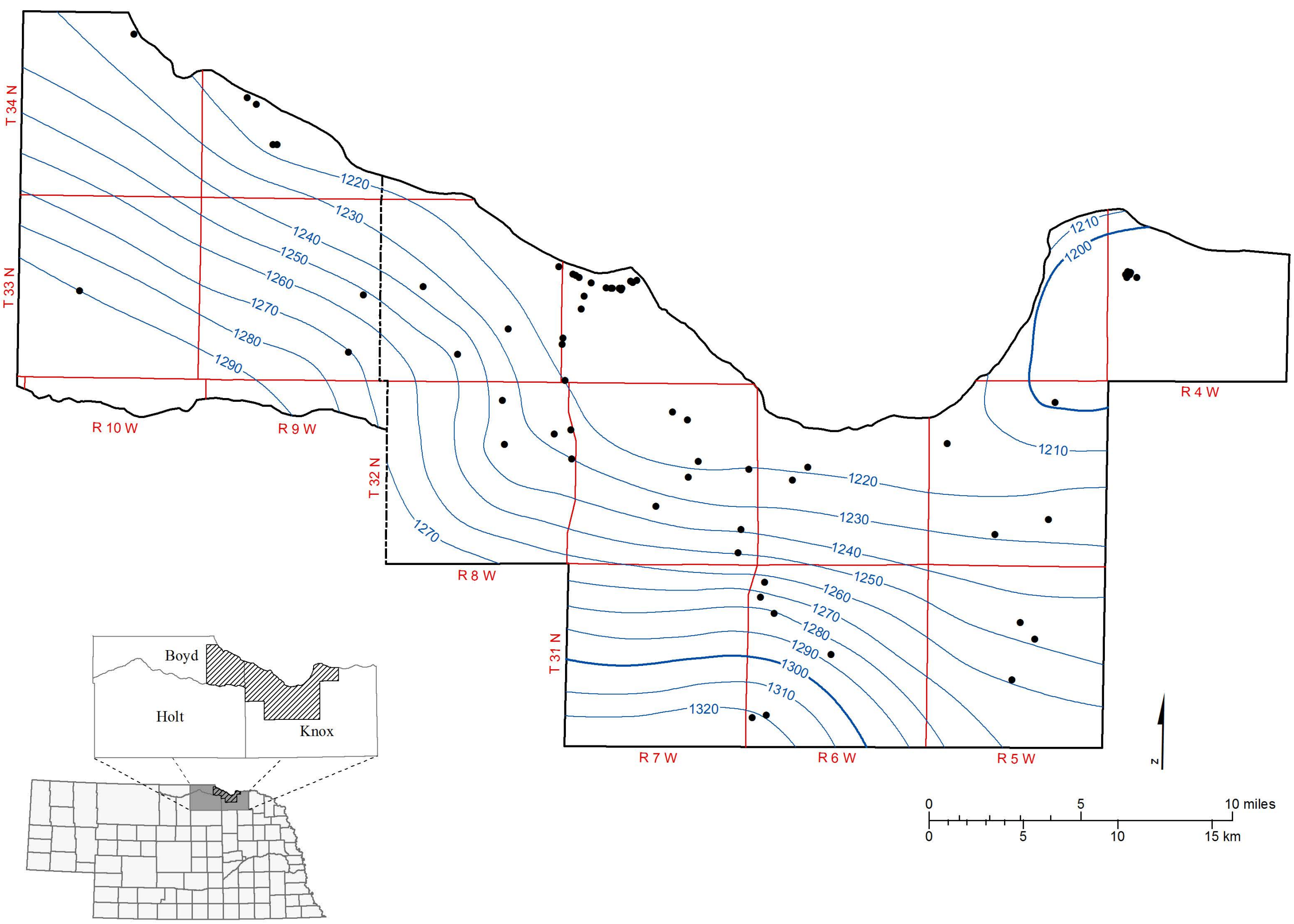


Figure 7. The estimated static water level in the Codell aquifer. Black dots represent registered wells from which the initial static water level measurement was used. The contours represent the potentiometric surface across most of the study area, except possibly in wells adjacent to the Missouri River, where the Codell aquifer may be unconfined. Contour interval is 10 ft.

Transmissivity

Transmissivity is an aquifer property that measures the rate of groundwater flow under a unit hydraulic gradient through a unit width of an aquifer over the saturated thickness (e.g. Kruseman and de Ridder, 1994). Transmissivity is directly measured using constant-rate pumping tests, but can be estimated using grain size (e.g. Piskin, 1971; Summerside et al., 2005; Divine, 2014). Figure 8 shows the estimated transmissivity of the Codell aquifer in the study area. The lithologic logs from 93 registered wells were used to calculate transmissivity values ranging from approximately 700 to 18,000 gpd/ft (1 to 26 cm^2/s). Only the 10,000 gpd/ft (14 cm^2/s) contour is depicted because the limited data set does not support more detail. The standard error on transmissivity maps estimated from grain size can be relatively high due to natural variation in lithology and subjective description of sediments on well logs (Divine, 2014). The 10,000 gpd/ft (14 cm^2/s) transmissivity contour generally corresponds to 50 ft (15 m) of Codell thickness. In the study area, thickness ranges from approximately 8 to 80 ft (2.4 to 24 m). A transmissivity value of 10,000 gpd/ft (14 cm^2/s) translates to a potential yield of about 100 gpm (6.3 L/s) in a large diameter well (Souders, 1967). Historic yields of public supply wells in or near Bon Homme County, South Dakota range from 80 to 100 gpm (5.0 to 6.3 L/s) (Jorgensen, 1971), which support the estimates depicted in Figure 8. Despite these estimates of potential yield, current active Codell wells are not large diameter and yield, on average, 15 gpm.

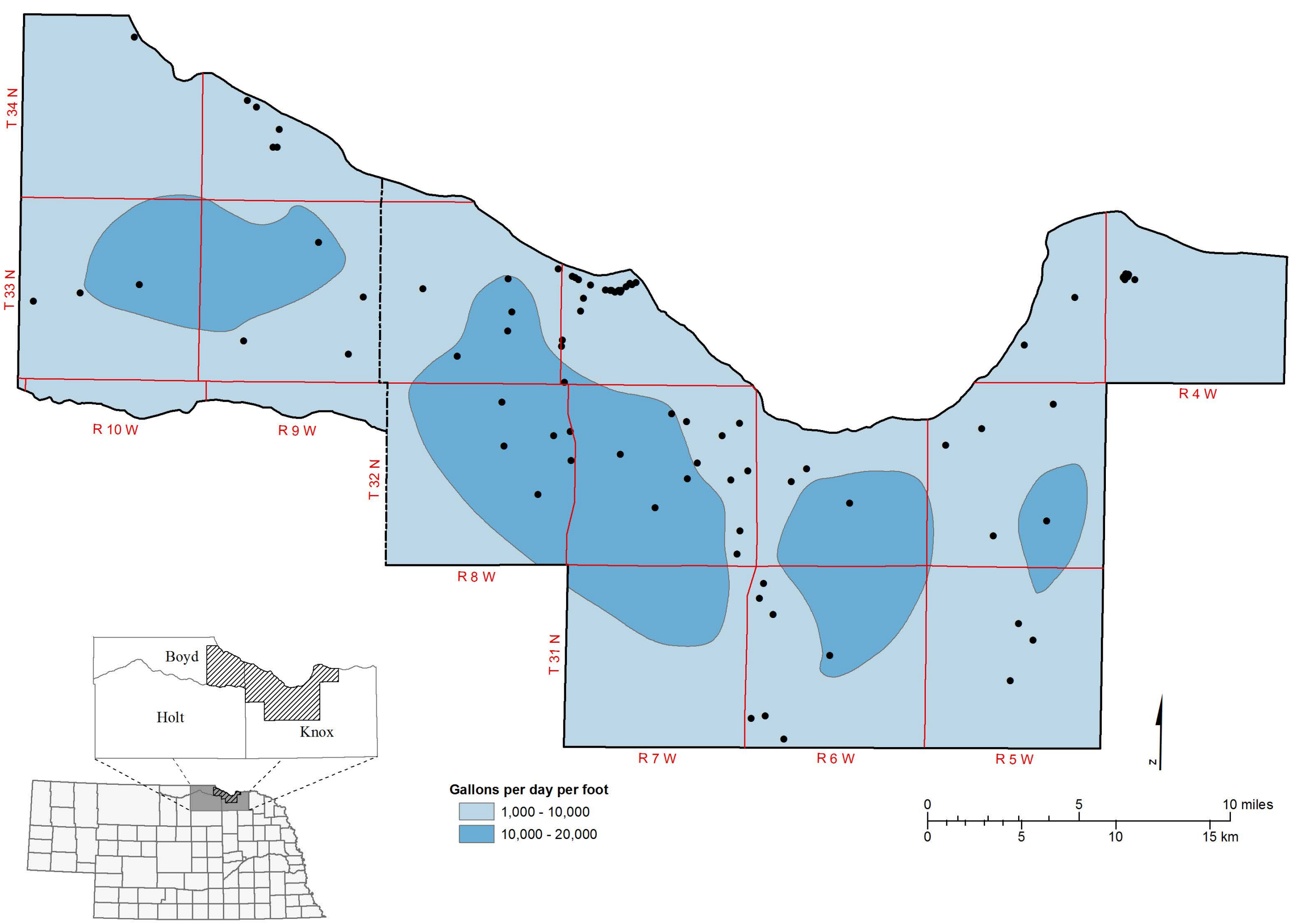


Figure 8. Transmissivity of the Codell aquifer. Black dots represent registered well logs used to estimate transmissivity based on grain size. A threshold value of 10,000 gpd/ft separates the study area into greater than and less than 10,000 gpd/ft.

Water Quality

The natural water chemistry in the Codell aquifer is variable, but it tends to be elevated in total dissolved solids, sodium, chloride, and sometimes sulfate, but also typically yields "soft water" that has low calcium and magnesium concentrations (Jorgensen, 1971; Kume, 1977; Dreeszen, 1966). Table 1 shows average water quality results from the Codell aquifer in Nebraska, South Dakota, and Kansas. The Nebraska samples are separated into two groups, one group collected in Boyd County and western Knox County by the Lower Niobrara Natural Resources District (NRD), and the other group collected in central Knox County by Lewis & Clark NRD (Fig. 9). The South Dakota samples are also separated into two groups, one group collected in Bon Homme County and the other in Charles Mix and Douglas counties.

A comparison of the results suggest that the water quality of the Codell differs within and between states (Table 1 and Fig. 10). Water quality samples from the Codell aquifer in western Kansas have a higher average calcium concentration relative to samples collected in South Dakota and Nebraska (Fig. 10). In Nebraska, the cation concentrations in samples collected in Boyd and western Knox counties by Lower Niobrara NRD are very similar to samples collected in Charles Mix and Douglas counties in South Dakota, the average cation proportions of both sample groups plotting in the sodium plus potassium apex of the cation plot in figure 10. The anion concentrations for these counties do not plot together, however, mostly due to differences in the sulfate, and to some degree, the chloride concentrations. The chloride concentrations in the 18 samples collected for this

		Well Locations				
Parameters (mg/L)	Recommended Limits[1]	Boyd & western Knox, NE[2]	Central Knox, NE[3]	Bon Homme, SD[4]	Charles Mix & Douglas, SD[5]	Western Kansas[6]
Well Depth (ft)	--	353	310	--	--	--
Year of Collection	--	2015	2015	~ 1970	~ 1977	1989
Number of Samples	--	8	10	≤ 33	≤ 30	25
Alkalinity	--	458	317	--	--	--
Bicarbonate	--	554	385	329	400	322
Boron	7	4.6	4.4	1.6	4.0	0.15
Calcium	--	15.8	86.9	80	30	125.0
Carbonate	--	0.05	0.14	12	--	--
Chloride	250	411	303	174	280	158
Fluoride	2	1.6	1.1	--	1.6	0.9
Hardness	--	65	358	--	120	322
Iron	0.3	0.1	0.1	--	0.8	1.4
Magnesium	--	6.3	33.7	18	8.8	29.5
Manganese	0.05	0.01	0.03	--	0.2	0.03
Nitrate	10	0.1	0.2	--	5.3	13.6
pH	6.5-8.5	7.9	7.7	--	7.9	7.5
Potassium	--	12.4	22.7	20	15	5.4
Silica	--	11.0	10.7	--	--	22.8
Sodium	30-60	437	266	356	460	145
Sodium Adsorption Ratio	--	--	--	15	22	--
Specific Conductance (micro-mhos)	--	2,240	2,040	2,030	2,200	1,107
Sulfate	250	27	234	410	380	158
Total Dissolved Solids	500	1,343	1,224	1,360	1,400	1,400

[1] U.S. EPA, 2012
[2] collected by Lower Niobrara Natural Resources District
[3] collected by Lewis & Clark Natural Resources District
[4] Jorgensen, 1971
[5] Kume, 1977
[6] Weigand, 1991

Table 1. Average concentrations of water quality parameters collected from the Codell aquifer in Nebraska, South Dakota, and Kansas.

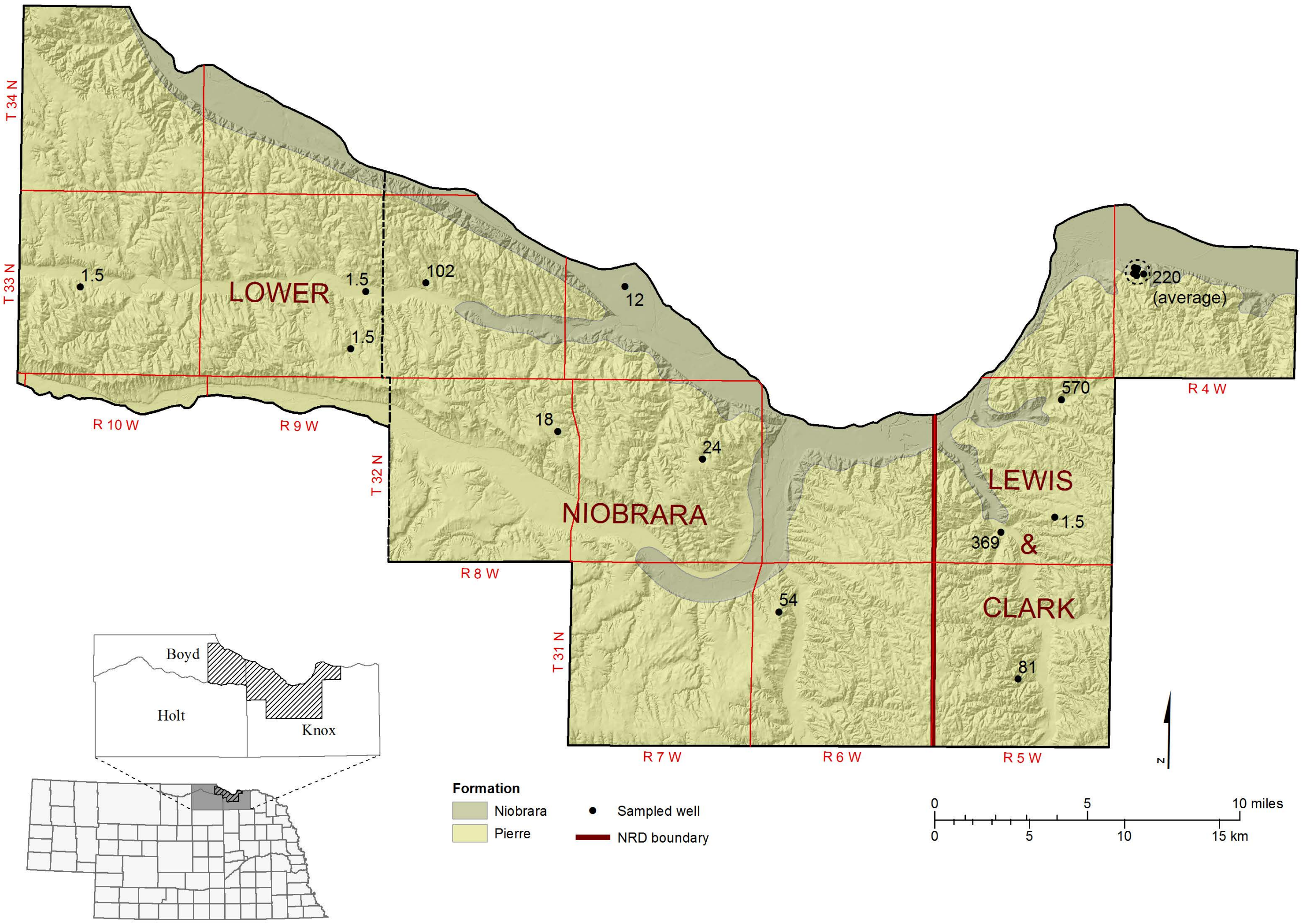


Figure 9. Locations of water quality samples collected in 2015 relative to topography and bedrock formations. The bedrock contact shown is approximate. Samples collected from wells located near the Pierre-Niobrara contact along valley walls may have higher sulfate concentrations relative to wells from other geomorphic settings. Numerical values show sulfate concentrations in mg/L.

study show a positive correlation with well depth using Spearman's rank correlation (correlation coefficient=0.53, p=0.025), indicating that chloride concentration increases with depth, a trend which may obscure other spatial patterns.

Pyrite deposits in the Pierre or Carlile shales are the most likely sources of sulfate in the Codell aquifer because the weathering of pyrite produces an acid solution enriched in iron and sulfate (Gosselin, 2001). Solutions naturally equilibrate toward neutrality, which is often achieved by ion exchange with clays (e.g. Drever, 1997; Gosselin, 2001). Joeckel et al. (2011) documented acid weathering of phyllosilicates at the contact between the Niobrara Formation and the underlying Carlile Shale in the vicinity of the study area and showed that it most often occurs due to lateral groundwater movement at geomorphic boundaries such as valley walls. In this study, the highest sulfate concentrations appear to correspond to wells located along drainages where the Niobrara Formation subcrops and the Carlile-Niobrara contact was probably subjected to the greatest amount of weathering, although the limited number of samples excludes definite correlation. Eight of the 10 samples collected in the central Knox sample group (including six samples in the village of Santee) are located in this geomorphic setting, but only one of the eight samples collected in the Boyd/western Knox sample group is so located (Fig. 9). This geomorphic dichotomy may be the cause of the order of magnitude difference in sulfate concentrations shown in Table 1.

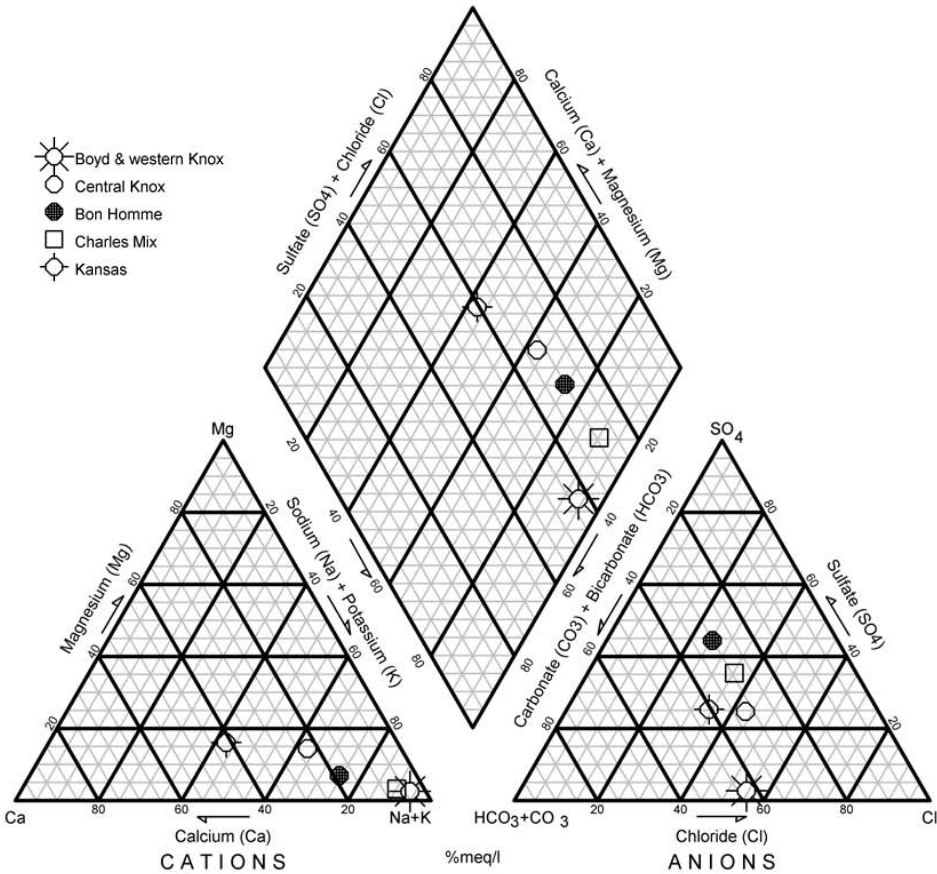


Figure 10. Piper diagram depicting water chemistry from recent and historic water samples collected from the Codell aquifer.

Recharge

Isotopic analysis of samples collected from the Cretaceous "Dakota aquifer" in the vicinity of the study area suggest that it was recharged in part with glacial melt water, possibly at Dakota Formation outcrops along the Sioux Quartzite Ridge, prior to and during the deposition of Pleistocene glacial sediments (Gosselin et al., 2001). The Carlie Shale was probably also subaerially exposed in Charles Mix and Bon Homme counties after pre-Illinoian stage erosion (Hedges, 1975) and it is possible that the Codell was also recharged with glacial melt water. Although the Missouri River Trench now appears to control the hydraulic gradient in the Codell aquifer and the current potentiometric surface excludes recharge from South Dakota to Nebraska, the entrenchment did not occur until Illinoian and Wisconsin times (Simpson, 1960; Christensen, 1974) and the aquifer was probably continuous prior to entrenchment.

The wells screened in the Codell aquifer in the study area average about 285 feet (87 m) in depth, and although they are confined, it is possible they could receive post-glacial recharge. Shallow aquifers in this area currently have elevated nitrate concentrations (e.g. Burbach and Spalding, 2000; Gosselin, 1990). The concentrations of nitrate in the Codell aquifer samples from the study area are near or below the detection limit (Table 1). Therefore, if local shallow aquifers recharge the Codell, the high-nitrate water either has not yet reached the study area or denitrification has occurred and the recharge water is not high in nitrate by the time it reaches the study area. More specific investigation, possibly including age dating and isotopic analysis, will be necessary to identify the recharge area(s) of the Codell aquifer in Nebraska.

SUMMARY

The Codell aquifer in northeastern Nebraska is an important resource to local residents but has not been previously studied, possibly due to its limited size and complex geologic setting. However, it is precisely because of the size and setting that hydrogeologic investigation is necessary to facilitate management of the resource. In northeastern Nebraska, the Codell aquifer underlies about 460 mi^2 (1,190 km^3) and hosts approximately 70 active registered domestic and stock wells. The average well depth is about 285 ft (87 m) and the average well yield about 15 gpm (0.95 L/s). The Codell Sandstone consists of up to three distinct sand or sandstone units, which are separated by thin shale units. The top of the Codell may be overlain by 0 ft to approximately 50 ft (0 to 15.2 m) of Carlile Shale with the two surfaces corresponding most closely in the western part of the study area.

The Codell Sandstone Member of the Carlile Shale was deposited on both the east and west margins of the Cretaceous Western Interior Seaway in a variety of near-shore marine and deltaic environments. The study area of this report is located along the eastern margin of the seaway, where the Codell was probably deposited as a prograding clastic wedge starting in southwestern Minnesota and advancing toward western Kansas during a sea level regression. Subsequent deformation and erosion altered the geometry of the Codell so that it now differs from its original shape and extent. The Codell aquifer in Kansas is not continuous with the Codell aquifer in South Dakota/Nebraska.

Structure contour maps of the Carlile-Niobrara contact and the top of the Codell Sandstone in the study area indicate that the two surfaces are similar in that they both dip generally to the south in the Knox County part of the study area. The shape of the surface roughly corresponds to Laramide structural deformation previously mapped at a different scale.

The static water level map of the study area indicates that the potentiometric head is highest (about 1,320 ft or 402 m) in the southern part of the study area and declines to approximately 1,200-1,210 ft (366-369 m) toward the Missouri River Trench. The Missouri River alluvium is a possible natural discharge for the Codell aquifer. The hydraulic heads in both South Dakota and Nebraska indicate that water in the Codell flows toward the Missouri River, although this configuration probably did not develop until the latter half of the Pleistocene when the Missouri River in the vicinity of the study area became entrenched in its current valley.

The transmissivity of the Codell in the study area varies from approximately 700 to 18,000 gpd/ft (1 to 26 cm^2/s). Only the 10,000 gpd/ft (14 cm^2/s) contour is depicted for the study area because the limited data set do not support more detail. The 10,000 gpd/ft (14 cm^2/s) contour generally corresponds to 50 ft (15 m) of Codell thickness. The average yield of active wells in the study area is about 15 gpm.

The water quality in the Codell aquifer is elevated in total dissolved solids, sodium, chloride, and sometimes sulfate, but also typically yields soft water that has low calcium and magnesium concentrations. Several of the analytes including calcium, sodium, magnesium and potassium are similar in concentration between South Dakota and Nebraska, although chloride and sulfate are not. The chloride concentrations measured in the 18 wells sampled for this study are positively correlated with well depth, while the sulfate results may have some relation to geomorphologic position in the landscape relative to zones of pyrite weathering in the Pierre and Carlile shales. The recharge area(s) for the Codell were not identified in this study, although it is possible that water in the Codell has both glacial and post-glacial origins.

DIRECTIONS FOR FUTURE WORK

Future data collection in the Codell aquifer should focus on quantifying changes in the potentiometric surface (both short- and long-term) and on identifying the recharge area(s). The localized and confined nature of the aquifer means that Codell wells are more susceptible to water level declines than wells screened in larger or unconfined aquifers. Installing dedicated monitoring wells in the Codell is advisable, although there are currently two Codell wells registered as inactive (one domestic and one stock, both in the Lower Niobrara NRD) that may be useful for periodic water level measurements or installation of pressure transducers, depending on the property owners' permission and future intent for use of the wells. Test hole logs described by geologists with accompanying downhole geophysical logs would also help constrain estimates of elevation, thickness, potential yield, and water levels in the aquifer.

Identification of the recharge area(s) will help to manage both water quality and quantity of the aquifer. Recharge may occur both laterally and vertically, but without knowing the possible recharge areas, changes to the rate and quality of recharge are impossible to predict. A recharge study would probably involve collecting water samples from Codell wells and assessing the age and isotopic composition of the groundwater. These data could then be compared to the water level change data to predict recharge areas. An airborne geophysical survey that maps the electrical conductivity of the subsurface might also be useful in identifying potential recharge areas. Isotopic and geophysical studies are not always conclusive, but given the current lack of data, the research would probably advance understanding of the aquifer.

Photo courtesy R.M. Joeckel, Conservation and Survey Division

The contact between the Carlile Shale (Kcbh) and the Fort Hays Limestone Member of the Niobrara Formation (Knfh) exposed along the south bank of the Missouri River in northeastern Cedar County near the mouth of Bow Creek. Person is 6.3ft (1.9m) in height.

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Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

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